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Teaching RC and RL Circuits Using Computer-supported Experiments

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Abstract

We suggest the study of the charging and discharging processes in the capacitor in an *RC* circuit and the rise and decay of current processes in an *RL* circuit using computer-interfaced experiments. This approach enables students to understand functions of *RC* and *RL* circuits through the visualisation of the processes, understand the use of computer interface for data collection, and speed up the data collection and their analyses. Using Excel for data analysis enables the verification of Kirchhoff's loop rule for the *RC* and *RL* circuits for each instant of time and the determination of time constants for the circuits through the graphical analyses.

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1. Introduction

Teaching physics for engineering students is always faced with the following questions: What material and physics concepts should be taught? What should be the teaching methodology to present this material? Below, it is suggested that students in general physics courses can use computer-interfaced experiments to facilitate the study of the charging and discharging processes of a capacitor in an *RC* circuit and the rise and decay of

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current processes in an *RL* circuit. The objective of this paper is to present an approach that enables students majoring in electrical engineering to apply the concepts learned in physics class to engineering problem-solving challenges. The goal is to facilitate students' transfer of knowledge from theory to engineering applications, thereby increasing student academic achievements. Physics remains the root of natural sciences, the theoretical basis of modern engineering and, more than any other science, promotes the development of creative and critical thinking in future engineers. Physics is an indispensable component in engineering curricula because it is based on our knowledge of physical laws. It is important that students understand that knowledge in physics is not limited to abstract issues but has actual applications in engineering and technology. Therefore, the transfer of knowledge from physics to engineering and technological applications becomes an essential factor to increase student academic performance, retention, and persistence through the understanding of important physics concepts [1].

Research in education in different countries shows that students at the college and even university levels continue to hold fundamental misunderstandings of the world around them. Science learning remains within the context of the classroom and just a small percentage of students are able to use the knowledge gained at school for solving various problems of the larger physical world [2, 3]. In most of the courses students hear lectures without strong connections to their everyday experiences. Physics cannot be taught only by using the book and blackboard and asking students to memorize rules, formulas and laws. One of the important parts of teaching physics is real-time laboratory experiments which students conduct during laboratory sessions as well as experimental demonstrations which visualize the laws of nature. The laboratory activities and experimental demonstrations should be established as a primary learning tool for students majoring in engineering at an early point in their academic careers so that students have a taste of the excitement of science and engineering research [3]. Therefore, it is necessary to promote teaching resources that support the understanding of physics concepts on one hand, and demonstrate their practical implementation on the other hand. Physics laboratory classes can be considered an important way to utilize this approach. Indeed, during laboratory class students perform experiments that illustrate and verify theoretical concepts presented in the lecture. Further implementation of these experimentally verified consents in some practical applications will show connections to students' everyday experiences. Therefore, the design of physics laboratory experiments should help students to understand main concepts and develop the critical thinking and problem-solving skills for the implementation of these concepts for engineering and technological applications [4].

An effective approach to teach physics today is to integrate computer technology into the physics laboratory. Since today's students are excited by computers and want to use them, computers must be an integral part of our physics laboratory and classroom. Computers will help students perform traditional experiments in less time and motivate them to become self-directed learners. Computers are part of the real word, so students must be prepared to use them. Furthermore, computers are helpful to instructors in the management of class time.

As the use of computers and sensors in physics laboratories has increased [5, 6], this paper offers computer-interfaced experiments related to *RC* and *RL* circuits that allow students to study the charging and discharging processes in a capacitor in an *RC* circuit and the rise and decay of current processes in an *RL* circuit, and provide the ability to readily transfer the material studied in physics to electrical engineering courses. The computer-supported experiments significantly simplify data collection, thus, reducing the time required to perform experiments and allowing students to plot more graphs in less time and include printouts of the graphs in their laboratory reports. Our approach enables the understanding of functions of *RC* and *RL* circuits through the visualization of the processes in these circuits. The paper is organized in the following way. In Sections 2 and 3, we present the main concepts for *RC* and *RL* circuits. The description of experiments and data analysis is given in Section 3. Finally, the conclusions follow in Section 4.

2. RC circuit

Materials for the study of time-varying current are presented in any general physics textbooks, see for example, Refs. 7 and 8. The best way for this to be studied is to consider a circuit consisting of a capacitor C and a resistor R connected in series, a source of emf ε, and a switch, as shown in Fig.1. A circuit containing a resistor and a capacitor is called an RC circuit. The system in Fig.1 is an electrical network, but it is not a circuit because there is no closed path. Let us see what happens when, at time $t=0$ s, the switch is closed to position *1*, thus creating the single loop circuit. When the emf ε is applied to the resistor R and the capacitor C in series, the charge q on the capacitor increases and the voltage $V_C(t)$ across the capacitor during the charging process is

$$V_C(t)=\frac{q}{C}=\varepsilon(1-e^{-\frac{t}{RC}})\text{, (charging a capacitor).} \quad (1)$$

The current through the resistor and the voltage across the resistor R during the charging process correspondingly are

$$i=\frac{dq}{dt}=\frac{\varepsilon}{R}e^{-\frac{t}{RC}}\text{ , } V_R(t)=iR=\varepsilon\, e^{-\frac{t}{RC}}\text{, (charging a capacitor).} \quad (2)$$

In Eqs. (1) and (2) $\tau_C=RC$ is the capacitive time constant of the circuit. When $t=\tau_C$ the charge has increased from zero to about 63% of its final value. Suppose we have waited long enough for the current to vanish. Now the capacitor in the circuit is fully charged to a potential equal to the emf ε of the battery. Once charged, the capacitor in the direct current circuit acts like an open switch in the circuit, in which it is placed. Since the fully charged capacitor acts like the open switch for DC current, there is zero current in the circuit. To discharge the capacitor, we need to move the switch to position *2*. When the switch is thrown from position *1* to position *2,* the capacitor can discharge through the resistance R, and the charge on the capacitor decays. The time derivative of the charge gives the current through the resistance

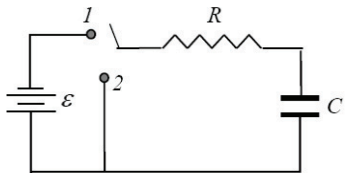

Fig. 1. A series RC network. There is no closed path, so that it is not yet a circuit.

$$i=\frac{dq}{dt}=-\frac{\varepsilon}{R}e^{-\frac{t}{RC}}\text{, (discharging a capacitor).} \quad (3)$$

We can find the voltage $V_C(t)$ across the capacitor and the voltage $V_R(t)$ across the resistor during the discharging process as

$$V_C(t)=\frac{q}{C}=\varepsilon\, e^{-\frac{t}{RC}}\text{ , } V_R(t)=iR=-\varepsilon\, e^{-\frac{t}{RC}}\text{, (discharging a capacitor).} \quad (4)$$

From equations (1) and (2) you can see that during the charging process the sum of the voltage $V_C(t)$ across the capacitor and the voltage $V_R(t)$ across the resistor is constant and equals ε. The same relationship you will get by applying Kirchhoff's loop rule for the charging process in the circuit in Fig.1 (the switch is closed to position 1), traversing it clockwise from the resistor

$$V_R(t)+V_C(t)=\varepsilon\ . \quad (5)$$

Eqs. (4) indicated that during the discharging process the sum of the voltage $V_C(t)$ across the capacitor and the voltage $V_R(t)$ across the resistor equals 0. You will get the same result by applying Kirchhoff's loop rule for the discharging process in the circuit in Fig.1 (the switch is closed to position 2), traversing it clockwise from the capacitor

$$V_C(t) - V_R(t) = 0\,. \tag{6}$$

2. RL circuit

Above we considered the circuit consisting of a capacitor C and a resistor R connected in series and a source of emf ε and demonstrated that if we suddenly remove the emf from the circuit, the charge does not immediately fall to zero but approaches zero in an exponential fashion. In addition, the time constant describes the fall of the charge as well as its rise. An analogous slowing of the decay or rise of the current occurs if we introduce an emf ε into a single-loop circuit consisting of an inductor L and a resistor R connected in series, as shown in Fig. 2. A circuit containing a resistor and inductor is called an *RL* circuit. The system in Fig. 2 is an electrical network, but it is not a circuit because there is no closed path. Let us see what happens when, at time $t=0$ s, the switch is closed to position *1*, thus creating the single loop circuit shown in Fig. 2. When an emf ε is applied to the resistor R and inductor L in series, the current in the inductor and resistor increases and the corresponding current and voltages are:

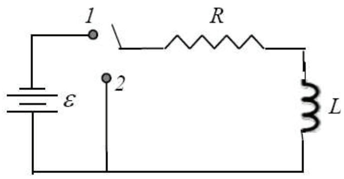

Fig. 2. A series RL network. There is no closed path, so that it is not yet a circuit.

$$i = \frac{\varepsilon}{R}(1 - e^{-\frac{R}{L}t})\,, \quad \text{(rise of current)}, \tag{7}$$

$$V_L(t) = L\frac{di}{dt} = \varepsilon e^{-\frac{R}{L}t}\,, \quad V_R(t) = iR = \varepsilon\,(1 - e^{-\frac{R}{L}t})\,, \qquad \text{(rise of current)}, \tag{8}$$

where $\tau_L = L/R$ is the inductive time constant of the circuit. Suppose we have waited long enough for the steady-state current in Fig. 2 to be established. Now the current in the circuit in Fig. 2 equals to ε/R. When the switch is thrown from position ***1*** to position ***2,*** in the circuit in Fig. 2, the emf vanishes and the current through the resistor R will decrease. However, it cannot drop immediately to zero but must decay to zero over time according to

$$i = \frac{\varepsilon}{R} e^{-\frac{R}{L}t}\,, \quad V_L(t) = L\frac{di}{dt} = -\varepsilon\, e^{-\frac{R}{L}t}\,, \quad V_R(t) = iR = \varepsilon\, e^{-\frac{R}{L}t}\,, \text{ (decay of current)}. \tag{9}$$

Eqs. (8) show that during the rise of current the sum of the voltage $V_L(t)$ across the inductor and voltage $V_R(t)$ across the resistor is constant and equals ε. At the same time Eqs. (9) indicate that during the process of decay of the current the sum of the voltage $V_L(t))$ across the inductor and voltage $V_R(t)$ across the resistor equals 0. The same relationship is obtained by applying Kirchhoff's loop rule for the processes of rise and decay of current. Therefore, Eqs. (5) and (6) are valid for the *RL* circuit, only the voltage $V_C(t)$ across the capacitor should be replaced by the voltage $V_L(t)$ across the inductor.

3. Description of experiments and data analysis

Computer-based experiments related to *RC* and *RL* circuits suggested below are developed for the study of charging and discharging processes in a capacitor in an *RC* circuit by measuring a voltage across a resistor and a capacitor as a function of time, as well as for the study the rise and decay of current processes in an inductor in an *RL* circuit by measuring the voltage across a resistor and inductor as a function of time. The experiments allow one to determine the time constant of a given *RC* or *RL* circuit and based on the measured and collected data to verify Kirchhoff's loop rule (5) and (6) for *RC* and *RL* circuits, respectively.

The circuit consisting of a capacitor *C* and a resistor *R* connected in series, a source of emf ε, and a switch provides two regimes: charging a capacitor and discharging a capacitor, as shown in Fig. 3. The experiments are designed to use the PASCO Science Workshop Interface box, Voltage sensors and *DataStudio* software [9]. The Voltage sensors plugs are connected into Analog Channel A and Analog Channel B on the Science Workshop Interface box and the Science Workshop Interface box is connected to the computer. For the *RL* circuit, the capacitor *C* shown in the diagram in Fig. 3 is replaced by the inductor *L*. Firstly, using the LCR meter, the resistance of the resistor, capacitance of the capacitor and inductance of the inductor are all measured. The *DataStudio* software allows one to measure, record and visualize on the computer screen the instantaneous value of the voltage across the capacitor *C* and resistor *R* for the *RC* circuit and voltage across the inductor *L* and resistor *R* for the *RL* circuit, correspondingly. The data collection occurs with frequency of 60 Hz. During the experiment students can see the fascinated colour pictures of the dependence of voltage across the resistor and capacitor on the time in the *RC* circuit and voltage across the resistor and inductor on time in the *RL* circuit. When data collection is finished students make a copy of the reading of the voltages recorded by the *DataStudio* software and paste it in the Excel worksheet and the results of the measurements of voltage versus time are analyzed using an Excel worksheet. They plot the graphs of the voltage across the resistor versus time ($V_R(t)$ *versus t)* and the voltage across the capacitor versus time ($V_C(t)$ *versus t)* for the charging and discharging processes in the *RC* circuit and actually obtain the pictures that they have in general physics textbooks (see, for example Refs. 6 and 7), and therefore, check and verify the validity of the corresponding equations listed in the textbook. Using an Excel worksheet for the voltages, students verify Kirchhoff's loop rule (5) and (6) for charging and discharging processes for each instant of time. The same analyses take place for the *RL* circuit by plotting the graphs of the voltage across the resistor versus time ($V_R(t)$ *versus t)* and the voltage across the inductor versus time ($V_L(t)$ *versus t)* for the rise and decay of current processes.

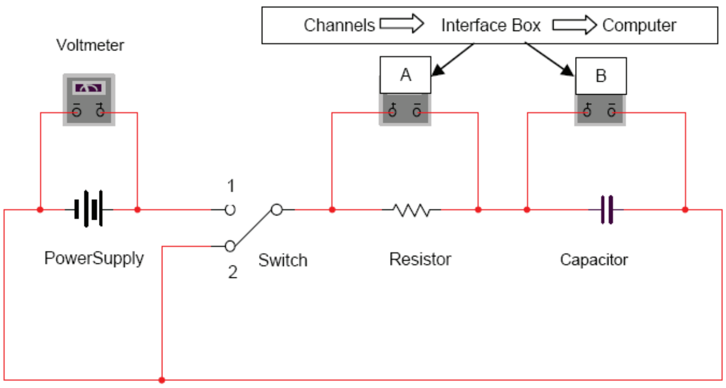

Fig. 3. Experimental setup for the *RC* circuit. For the *RL* circuit the capacitor *C* shown in the diagram should be replaced by the inductor *L*.

At the next step, the time constant can be determined for the *RC* and *RL* circuits. Using Excel, one can calculate $\ln(V_R(t)/\varepsilon)$ for the charging process and $\ln(V_C(t)/\varepsilon)$ for the discharging process and plot the graph of $\ln(V_R(t)/\varepsilon)$ versus time *t* and $\ln(V_C(t)/\varepsilon)$ versus time *t*. The values of the slopes for these graphs for the charging and discharging processes is equal to $1/RC$ allows determining the time constant $\tau_C = RC$ for the charging and discharging processes as the reciprocal of the slope. For the *RL* circuit calculate $\ln(V_R(t)/\varepsilon)$ for the rise of current process and $\ln(V_L(t)/\varepsilon)$ for the decay of current process and plot the graph of $\ln(V_R(t)/\varepsilon)$ versus time *t* and $\ln(V_C(t)/\varepsilon)$ versus time *t*. The value of the slopes for these graphs for the rise and decay of current processes is equal to R/L and allows the time constant $\tau_L = L/R$ to be determined for the rise and decay of current processes as the reciprocal of the slope.

4. Conclusions

In the suggested experiments, students gain knowledge of electronic equipment, interface of the computer with the actual physics experiment, and use Excel for the calculations, analysis and plotting graphs. Most important is that these experiments demonstrate and allow students to determine the time constants for the charging and discharging processes and the rise and decay of current processes and, therefore, to bring abstract concepts to the reality. At the next step students change the values for the capacitance and resistance and visually observe how the time constant for the *RC* circuit depends on *R* and *C,* as well as by changing the values for the inductance and resistance, examine how the time constant of the *RL* circuit depends on *R* and *L*. After performing these experiments, an instructor can then more effectively discuss and demonstrate the applications of *RC* and *RL* circuits in electrical engineering or performs some experimentation with the *RC* and *RL* circuits related to practical applications.

In addition, performing these experiments provide students with the opportunity to utilize the computer as a powerful tool in the process of collecting and analyzing data, as well as displaying and analysing data graphically. The computer interface significantly simplifies data collection, thus reducing the time required to perform the experiments and allowing students to plot more graphs in less time and include printouts of the graphs in their laboratory reports. This conclusion is also based on the analysis of students' performance of computer-based experiments presented in Refs. 5, 6 and 10. The computer also helps students analyze their data quickly and efficiently. The result is a shift of focus – students now can spend more time interpreting their graphs, studying the relationships between variables, and understanding the physical concepts being investigated. Furthermore, computers are helpful to instructors in the management of class time. The time saved may be devoted to more detailed explanations of the physics concepts behind the experiments.

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